m, and of those experiments, is something that discussed, in this Journal[8] and elsewhere.

egacy of Bell's theorem, a curious one and not welcome one, is that it seems to have brought odwork a nontrivial number of people (some ors and would-be authors) who do not seem to in equations or vacuum pumps but are ena- the notion of analogies (or more) between ics and mysticism, who like to utter sentences uch as "EPR experiment," "the downfall of ," and the like. Do they understand the mean- rds they use? Do they know, as Bernstein has "Bell's theorem is not a mantra, it is a r, one might ask, do they know that Aspect's s not a happening or an encounter, not even a periment, but an *experiment*?

some remarks that are often quoted that con- ary impression, I am sure that Einstein always he primacy of experimental results. He might have been *happy* about the results of the recent echanical experiments, but he surely would *terested*, and I am certain that he would have ed that John Bell, by suggesting experimental t intellectually respectable to worry about the of quantum mechanics. Not long ago, I read a Bell with the title "The man who proved Ein- ong." I think that title is at best misleading. I d be more accurate to describe Bell as the man hat *Pauli* was wrong, that *Einstein* was right. I to suggest, of course, that Einstein was right in that God does not play dice with the universe, demonstrated the validity of hidden-variables nything of the sort; if anything, the opposite is do mean to say is that Bell showed that Ein- ht in maintaining his interest in foundational urging that other physicists should also be regarding such questions as a legitimate part hich might someday be put to the test of exper-

Robert H. Romer, *Editor*

[1]J. S. Bell, "On the Einstein–Podolsky–Rosen paradox," Physics **1**, 195–200 (1964); reprinted in J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge, New York, 1987), and in *Foundations of Quantum Mechanics since the Bell Inequalities—Selected Reprints*, edited by L. E. Ballentine (American Association of Physics Teachers, College Park, MD, 1988).

[2]Martin J. Klein, *Paul Ehrenfest, Vol. 1, The Making of a Theoretical Physicist* (North-Holland, Amsterdam, 1970), p. 44.

[3]David Bohm, *Quantum Theory* (Prentice-Hall, New York, 1951).

[4]Reference 3, Chap. 22.

[5]Jeremy Bernstein, *Quantum Profiles* (Princeton U.P., Princeton, 1991), p. 76.

[6]"When I was a student I had much difficulty with quantum mechanics. It was comforting to find that even Einstein had had such difficulties for a long time. Indeed they had led him to the heretical conclusion that something was missing in the theory." J. S. Bell, "On the impossible pilot wave," Found. Phys. **12**, 989–999 (1982); reprinted in *Speakable and Unspeakable in Quantum Mechanics*, Ref. 1.

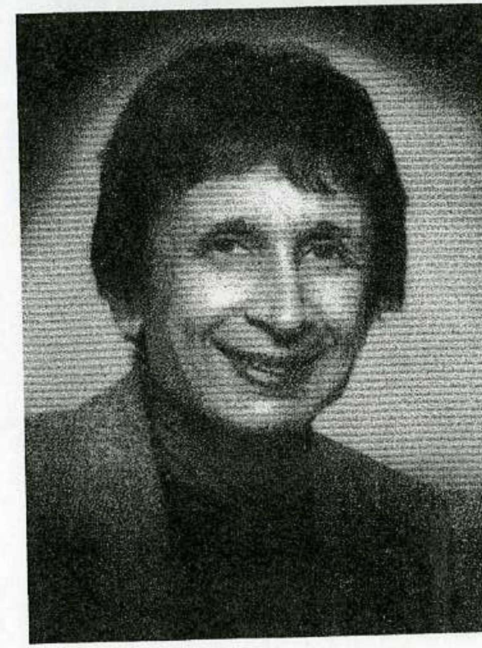
[7]Indeed, Bell went further, expressing misgivings about contrived *experiments*, carried out within the confines of a mere physics laboratory. "In the beginning natural philosophers tried to understand the world around them. Trying to do that they hit upon the great idea of contriving artificially simple situations in which the number of factors involved is reduced to a minimum. Divide and conquer. Experimental science was born. But experiment is a tool. The aim remains: to understand the world. To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation will not exclude the big world outside the laboratory." J. S. Bell, "Against 'measurement,'" CERN report CERN-TH-5611/89; reprinted in *Sixty-Two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*, edited by Arthur I. Miller (Plenum, New York, 1990). See also Phys. World **3**(8), 33–40 (1990).

[8]N. David Mermin, "Quantum mysteries revisited," Am. J. Phys. **58**, 731–734 (1990); Daniel M. Greenberger, Michael A. Horne, Abner Shimony, and Anton Zeilinger, "Bell's theorem without inequalities," Am. J. Phys. **58**, 1131–1143 (1990).

[9]Reference 5, p. vii.

[10]John Gribbin, "The man who proved Einstein was wrong," New Sci. **128**, (1744), 43–45 (1990).

Lillian C. McDermott: Recipient of the Robert A. Millikan Lecture Award



With the Robert A. Millikan Lecture Award we honor one of our teachers among teachers. I use that phrase because this person's contributions go beyond the direct interaction with her students. This person is teaching us; teaching the teachers of physics. The Robert A. Millikan Lecture Award is given for "notable and creative contributions to the teaching of physics." This year's awardee is Dr. Lillian McDermott from the Physics Department of the University of Washington.

Lillian C. McDermott received her Ph.D. in experimental nuclear physics from Columbia University in 1959. She was born in New York City and did her undergraduate work at Vassar College. In 1961, she became an instructor at City College in New York. She left this position in 1962 to move to Seattle and taught at Seattle University from 1965–1969. She has taught at the University of Washington since 1967. She began a full-time appointment as assistant professor in 1973 and has been a full professor since 1981. She is currently director of the Physics Education Group, in which students earn the Ph.D. in physics for research in physics education.

Her current research is on identifying and addressing specific difficulties students have in learning physics. Lillian does something that all physics teachers claim to do, only she does it with the care of a researcher in search of fundamental answers. Her papers usually start with the phrase, "Student understanding of..." or "Student difficulties with..." In these papers she shares the insights of her exceptional research, insights that all of us who profess to be physics teachers should have deeply ingrained in our world views. She shows us that concepts that we think we are teaching, that we think we are testing on, and that we think students understand, just are *not* getting across to our students. When you look at the students' understandings a different picture emerges. That new picture is largely a result of Dr. Lillian McDermott's quest for truth.

It gives me great pleasure to represent the AAPT Awards Committee of the American Association of Physics Teachers and your colleagues in presenting you as the 1990 recipient of the Robert A. Millikan Award "for notable and creative contributions to the teaching of physics."

Gerald F. Wheeler
Chair, AAPT Awards Committee
28 June 1990

Millikan Lecture 1990: What we teach and what is learned—Closing the gap

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I. INTRODUCTION

Today science education is one again *enjoying* a period of crisis. The verb has been deliberately chosen for its positive connotation. Appropriate or not, frequent reference in the media to a crisis has generated an environment that is highly supportive of efforts to improve the teaching of science and mathematics. At the precollege level, a multitude of projects are attempting to bring about change both by formal means, through academic institutions, and in informal ways, through museums and the media. The situation at the college level, though less dramatic, is nevertheless one of ferment. There is considerable enthusiasm for the development of new instructional materials for a variety of college populations, ranging from committed science and engineering majors to general education and liberal arts students.

The current flurry of activity is not unprecedented. Recurring periods of dissatisfaction with the state of physics teaching in the past have motivated instructors to develop new curricula. Generally the pattern has been the same: an initial period of eager adoption is followed by a decrease in

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ith the passage of time, enthusiasm wanes and ment sets in. Eventually, the situation degener- ently to give rise to another round of concern ginning of another cycle. The reform movement d after the launch of Sputnik in 1957 is an exam-

the late 1950s and 1960s, science in elementary school consisted mostly of reading and memo- high school, as in college, the curriculum in s generally considered to consist of a course syl- t, a collection of standard problems, and a set of laboratory experiments. Motivated by the chal- utnik, physicists and other scientists initiated develop new instructional materials for elemen- iddle-school students. Support was provided by cience Foundation. Basic to all of the projects cognition that a curriculum properly includes content to be taught but the manner in which it he goal of the developers was not to write new texts in which students could learn facts nor to eriments through which students could verify lts. The goal was to produce innovative curricu- ld be inquiry oriented and activity centered so ts would have the experience of actively partici- e scientific enterprise.

f high quality and initial promise, the national e materials that were developed fell far short of en anticipated. Memories still linger of the hal- putnik period of progress and its abrupt termi- the cessation of NSF funding for all but gradu- n. Comparisons with present-day practice are g. The original curricula are currently being on a small scale. They have left a legacy, how- form of "hands-on" activities included in some commercial texts. Unfortunately, the spirit of mostly vanished from many contemporary which tend to be encyclopedic in their coverage. se activity in precollege curriculum develop- the Sputnik era was accompanied by work on ale at the undergraduate level. A series of na- rences encouraged individual faculty to pro- structional materials for teaching introductory sics. However, the constraints were such that ction continued in the traditional manner.

TCH OF CURRICULUM

s instructors, we may feel that we cannot af- go the present opportunity for bringing about we are also likely to be skeptical. In light of past is there a basis for believing that we can be more he future? We begin trying to answer this ques- ing the suggestion that many of the problems in cation have been exacerbated by a curriculum been well matched either to the students or to r, or both. Consider the following analysis of r cycle of curriculum development.

e instruction

er in which the elementary and early middle- rials were developed during the post-Sputnik d the likelihood that they would be suitable for l population. Tested continually in the class- ghout the period of design, ESS, SCIS, and SAPA were, on the whole, well matched on the interests and abilities of children.[1] The main reasons for the failure of these curricula to be widely adopted and sustained was that a good match was never achieved between the instructors (in this case, the precollege teachers) and the curriculum. Too little attention was devoted to the preparation of teachers. The belief that the instructional materials were "teacher proof," i.e., that it was not necessary for the teacher to have achieved prior mastery to teach a particular topic, proved to be erroneous. The expectation that teachers would learn along with their students was unrealistic. The gap between the intellectual demands of the subject matter and the preparation in science of most elementary and middle-school teachers was too great to be closed without the help of knowledgeable instructors. Self-directed "hands-on" experience and teacher's guides were not enough.

The importance of adequate teacher preparation was also underestimated in curriculum development projects for upper middle school and high school. According to a recent national survey, approximately one-third of the teachers of physics in high school have neither majored in physics nor taught the subject as a primary teaching assignment long enough to develop subject matter competence.[2] The common assumption that underprepared teachers can acquire through lectures the background they are missing is not valid. To be able to teach science as inquiry, teachers need to be given the opportunity to learn in much the same way as their students.

Mismatch with the instructor (in this case, the precollege teacher) was only one facet of the problem encountered in upper middle school and high school in the implementation of curricula developed with NSF support. Although designed by, and much respected by, the physics community, these materials often proved to be beyond the capacity of the majority of students for whom they were intended. For example, the developers of IPS planned that program for the seventh and eighth grades.[3] In fact, it proved to be a better match to the ability of ninth-grade students. PSSC Physics and Project Physics were not as effective as had been hoped because both programs, especially PSSC, turned out to be well matched only to the more able students.[4]

B. Introductory college course

At the college level, the match between instructor and curriculum has always been extremely good. For the most part, the curriculum has been designed by faculty who think of students as very much like themselves. The traditional introductory physics course worked well for them as it still does for many physics majors, typically about 1 out of every 30 students in the class. Sufficient numbers of science and engineering majors pass the course with acceptable grades. However, there is considerable evidence that the curriculum is not well matched to many students in the introductory course. A large number are inadequately prepared for the level of instruction. Unfortunately, a disproportionate percentage of minority students falls into this category. How many potential physicists and other scientists are lost from the ranks because they are not able to understand the material at the complexity and pace of the typical course is not known. However, it is known that often well-prepared students withdraw from science and engineering majors not because they think that the course

work is too difficult, but because it is uninteresting and of little value.[5] In other words, there is evidence that the curriculum may not be appropriate for either the poorly prepared or the well prepared. Prospective teachers are in a particularly difficult position. They may be expected to teach a curriculum to which they will not be well matched as instructors, after having learned from a curriculum to which they were not well matched as college students.

III. GOALS OF INSTRUCTION

The design of an effective course requires the identification of instructional goals. Some of these will depend on the background and aspirations of the students: on whether the course is intended for those majoring in physics or engineering or for those satisfying a general education requirement. Many universities also offer other courses for students with varying degrees of mathematical preparation. Among those enrolled in introductory courses are students who will become teachers of physics in high school and some who will teach (or avoid teaching) physical science in elementary and middle school.

Although the needs of different student populations vary, there is a common core of intellectual issues that are important in planning all instruction at the introductory level. Of greater importance than the choice of specific topics are questions such as the following: What value should we place on the acquisition of descriptive knowledge as contrasted with scientific reasoning skills? Do we expect students to develop sufficient proficiency in qualitative reasoning to be able to interpret new physical situations in terms of the concepts that have been developed? Do we want students to view science as static knowledge—a body of established facts, or as a dynamic process—a way of finding out about the natural world? How much emphasis should we place on *how* we know as distinct from *what* we know? How important is it that students learn to recognize what is and what is not scientific evidence, what is and what is not a scientific explanation? It is not easy to give definitive answers to such questions. The manner in which we attempt to resolve them determines the balance between content and process, and therefore the nature of the curriculum.

A. Intellectual objectives

There are some basic objectives for an introductory physics course that most instructors would agree are important. Having completed such a course, students should have acquired a sound understanding of certain basic physical concepts that they can define operationally and link in a meaningful manner to important principles. They should have developed facility with formal representations (diagrams, graphs, equations, etc.) and be able to describe in detail the relationship between a concept and the formalism that is used to represent it. They should have developed sufficient proficiency in scientific reasoning (proportional, analogical, model based, etc.) to apply the concepts and representations of physics in the analysis and interpretation of simple phenomena. Students should be able to make explicit the correspondence between a concept or a representation and an actual object or event in the real world. It is, of course, also necessary that students in an introductory course learn how to solve physics problems. We have found, however, that important intellectual objectives are often ignored when instruction is geared toward problem solving. Students tend to concentrate on algorithms rather than on the subject matter.

B. Student attainment

Does the traditional curriculum in physics promote the type of understanding that has been outlined? Does meaningful learning take place in the sense that students are able to apply concepts and reasoning skills in situations that are similar, but not identical, to the context in which they were developed? There is considerable evidence that indicates that for many students the standard introductory courses are not effective in helping achieve the kinds of intellectual objectives under discussion. Ease in using technical vocabulary does not indicate conceptual understanding. The ability to follow certain prescribed procedures for solving standard problems does not indicate development of scientific reasoning skills. Although the claim is often made that physics helps students develop ability in critical thinking, the traditional curriculum seems to fulfill this function only for students who have already made a good start before beginning the course.

The difficulties students have in physics are not usually due to the failure of instructors to present the material correctly and clearly, at least as the delivery of information is viewed from the perspective of a physicist. What is taught is not usually wrong, although occasionally this may be the case. Unfortunately, even lucid presentations may not be effective. What the instructor says or implies and what the student interprets or infers as having been said or implied are not the same. There are often significant differences between what the instructor thinks students have learned in a physics course and what students may have actually learned.

IV. CURRICULUM DEVELOPMENT

To be effective, a curriculum must meet students at their present state of intellectual development and help them gradually deepen their understanding. The incompatibility between the curriculum and the students in introductory physics seriously hampers the effectiveness of instruction.

A. Traditional approach

Traditional instruction in physics, both in high school and in the introductory college course, has been based on the instructor's view of the subject and on the instructor's perception of the students. The same instructional materials may appear very different to instructors than to students. A major part of the appeal of physics to a physicist is the generalization and synthesis about the natural world that an understanding of the subject makes possible. Physicists often find exhilarating the sense of intellectual power that results from being able to predict the outcome of change, either internally generated or externally imposed, on a physical system. There is an aesthetic satisfaction in being able to explain a multitude of apparently unrelated, diverse phenomena in terms of a few basic principles. In recalling how they were inspired by their own experience with introductory physics, many instructors tend to think of students as younger versions of themselves. In actual fact, such a description fits only a very small minority.

sics instructors are conscientious and have a mitment to their subject. They are eager to h their knowledge and their enthusiasm to stu- ng obtained a particular insight after hours, s, or years of intellectual effort, they want to owledge with their students. To save students f having to go through the same struggles they nced, physics instructors often teach from the om the general to the particular. Generaliza- en fully formulated when they are introduced s are shown how to apply them to specific ex- y little inductive thinking is involved; the rea- nost entirely deductive; the student is not ac- ged in the process of abstraction and on. By presenting students with a few general nd showing how these can be applied in a few , instructors hope to teach students to do the situations. As a result of this experience, it is tudents will not only acquire specific knowl- lls but also come to appreciate the beauty and he physicist finds in physics.

m development, for both high school and col- ly reflects the attitudes and practices that typi- terize physics instruction. The problem with al approach is that it ignores the possibility eption of students may be very different from nstructor. Perhaps at their stage of develop- students are not prepared to learn what we o learn from the physics curriculum that we .

urces

are in a better position than ever before to sk of improving the match between students um. There have been two developments since of reform that provide a basis for optimism succeed.

cs education, the most significant difference present situation and the post-Sputnik era is body of knowledge about student understand- s. The learning and teaching of physics as a cholarly inquiry is a relatively new field. The des have seen the growth of an international engaged in research in physics education.[6] gnitive psychologists, and science educators volved. Each of these groups has a different (See Fig. 1.) In keeping with their role in the f precollege teachers, science educators focus the development and testing of methods for nce. Although physics may provide the con- l of research is likely to be an instructional heory of instruction not specific to physics. ychologists take a different approach. They students solve physics problems to gain in- man thought processes. Sometimes computer sed as an aid in the analysis of problem-solv- The ultimate objective may be to develop a gnition. For cognitive psychologists and ators, interest in physics as a discipline is he driving force. Nevertheless, these groups e to our knowledge of student difficulties. group engaged in research in physics educa- of physics instructors, whose primary motiva- om an intellectual commitment to the subject

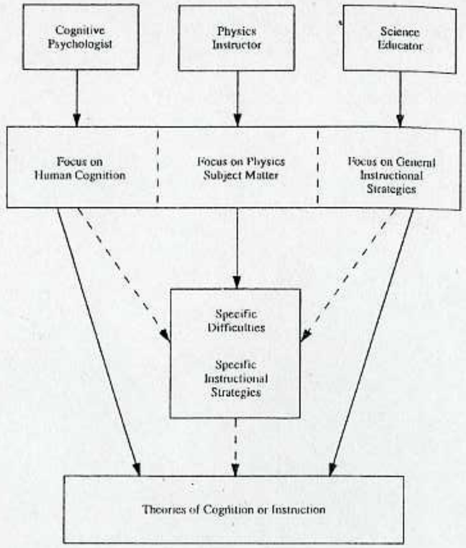


Fig. 1. Perspective on research in physics education.

itself. The main impetus for their research is the desire to improve instruction in physics, although they may also be peripherally interested in theories of cognition or instruction. Physicists are much more likely than science educators or cognitive psychologists to be able to explore student understanding of physics in depth. They have the background necessary to recognize and interpret subtle, yet important, differences between what we teach and what is learned. The results from research by those who know the subject matter well can provide a rich resource for curriculum development.

A second important development since the post-Sputnik era of curriculum reform is the enormous advance in technology that has taken place. Today, the computer offers the possibility, along or in conjunction with other devices such as a videodisk or microcomputer-based laboratory tool, to teach physics in new ways. It is possible that this new resource may enable us to individualize instruction in large lecture courses. Many physics instructors are active proponents for increased use of the computer in physics education. They are producing instructional software at a rapid rate. However, experience has shown that many computer programs are not well matched to the needs or abilities of students. To be able to realize the full potential of the new technology, we must understand both how students learn physics and how the computer can best be used as an aid in the process. There is a need for research to help insure that computer-based instructional materials will become a useful resource for the teaching of physics.

C. Constructivist approach

Perhaps the most significant effect that research in physics education has had on physicists working in this area has been to impress upon them the necessity of focusing greater attention on the student. Constructivist epistemology provides a theoretical basis for such an approach.

In nontechnical terms, we can briefly summarize the constructivist view of how scientific knowledge is acquired as follows: All individuals must construct their own concepts, and the knowledge they already have (or think they have) significantly affects what they can learn. The student is not viewed as a passive recipient of knowledge but rather as an active participant in its creation. Meaningful learning, which connotes the ability to interpret and use knowledge in situations not identical to those in which it was initially acquired, requires deep mental engagement by the learner. The student mind is not a blank slate on which new information can be written without regard to what is already there. If the instructor does not make a conscious effort to guide the student into making the modifications needed to incorporate new information correctly, the student may do the rearranging. In that case, the message inscribed on the slate may not be the one the instructor intended to deliver.

V. RESEARCH AS A GUIDE FOR CURRICULUM DEVELOPMENT

The usual measures of assessment common to physics courses—the ability to state correct definitions, reproduce proofs, solve standard problems—cannot provide sufficiently detailed information to determine to what degree students achieve the intellectual objectives mentioned earlier. Neither does feedback from the traditional forms of testing provide an adequate basis for deciding how to improve the match between curriculum and student. There is a need to learn what students actually understand as opposed to our perception as instructors of what they understand. The main body of this paper is on the use of research as a guide for curriculum development. The context for this discussion is the experience of the Physics Education Group at the University of Washington.

The group has for many years been engaged in a coordinated program of research, curriculum development, and instruction. The faculty, research associates, and graduate students in the group participate in all of these components. The graduate students do research in physics education to earn the Ph.D. in physics. Application of the results of research to the development of curriculum is a major activity of the group. Besides teaching undergraduates from the general population, we conduct special instructional programs. For more than two decades, we have been offering physics courses for both preservice and inservice teachers at all precollege levels. We have also developed a special preparatory program to help undergraduates with a weak science background succeed in the mainstream physics courses that are the gateway to science-related careers.

A. Approach of Physics Education Group

We recognize that for students to acquire a functional understanding of physics they must be active participants in the learning process. We take a generally constructivist approach but resist the label because we feel it falls short in characterizing our position. A major challenge in curriculum development is to determine just how much guidance is the right amount to achieve the necessary level of interest and involvement. If the instructor, computer, or text assumes either too large or too small a role, there is a danger that students will not become intellectually engaged at a deep enough level to be able to transform the material into a meaningful and useful form. Rote memorization may replace the development of both conceptual understanding and scientific reasoning ability.

We think of the curriculum holistically: as the integration of content (syllabus, text, problems, laboratory experiments) and the way in which it is taught. We search for a balance between content and process, between science as knowledge and science as a way of knowing. We try to produce curriculum that is well-matched to students through a three-part process: (1) we conduct systematic investigations into how students think about physics before, during, and after instruction; (2) we use the results of this research to guide the development of curriculum; and (3) we design, test, modify, and revise our instructional materials in a classroom setting, in which detailed feedback from students is continuously available. We consider research, curriculum development, and instruction as components of a continuous, interactive, and iterative process.

B. Methods of research

The individual demonstration interview is the primary data source in investigations of student understanding conducted by the Physics Education Group.[7] A simple demonstration, which may involve real equipment or computer simulations, serves as the basis of a dialogue between an investigator and a student. In a typical interview, the investigator might ask the student to predict how certain alterations in the apparatus would affect the demonstration, or to specify what changes in the setup would produce a particular effect on the demonstration. Explanations of reasoning are elicited from the student throughout the interview, which lasts from 30 to 45 minutes. We try to identify specific student difficulties through a detailed analysis of interview transcripts.

The constant presence of students in our own classes and our easy access to students in the department's standard courses make it possible for us to conduct research in the naturalistic setting of the classroom as well as the more formal interview environment. These more broadly based descriptive studies often involve much larger numbers of students than would be possible through interviews. Data are in the form of observations of students working in the laboratory, homework assignments, examinations, class discussions, dialogues between students and instructors, and conversations among students. In some cases, we can monitor student achievement over an extended period, a type of research that is more difficult to do with interviews.

In Secs. VI–VIII we discuss three ways in which the Physics Education Group is using research to try to improve the match between the curriculum and the students. In Sec. VI, we demonstrate by means of specific examples how we have applied findings from our investigations of student understanding in the development of a laboratory-based curriculum. In Sec. VII, we describe a new direction in our research by illustrating how we attempt to identify difficulties that students may encounter with individual elements of the traditional curriculum, such as a standard problem, demonstration, or laboratory experiment. In Sec. VIII we comment on some recent research in which we examine the potential of the computer, both as a means of instruction and as an investigatory probe of student understanding.

ELOPMENT OF A LABORATORY-BASED ULUM

ection, we describe the role research has played lopment of curriculum by the Physics Education part of a long-term project, we have produced a atory-based module collectively entitled *Physics* [8] Since we have selected the content of this curri- he basis of our research and teaching experience, characterize this development effort as a "bot- pproach, i.e., as proceeding from the needs of the design of curriculum.

of laboratory-based instruction

um development by the Physics Education been primarily laboratory based and inquiry ur experience indicates that it is much easier to lents intellectually in a learning situation that is ntered than in a traditional laboratory/lecture wever, we have additional reasons for choosing an inquiry-oriented, laboratory-based curricu-

g materials for the preparation of precollege s been a major activity in our group. Most nd to teach as they have been taught. Science for young children is known to be more effec- oncept development is based on concrete expe- recognize that if we want teachers to be able to s kind of instruction, we must give them the to learn in a "hands-on" manner.

eing appropriate for teachers, laboratory-based also works well with other populations. We *Physics by Inquiry* useful in helping underpre- nts strengthen their reasoning skills. The mod- so been used with liberal arts students, who we learn more about the nature of physics from n in scientific inquiry than from courses on poets."

ur interest in research has been a major motiva- eloping an inquiry-oriented, laboratory-based Regular contact with students as they work uipment allows us to supplement the informa- d from formal investigations. There is a con- tunity to observe students and to engage them l Socratic-style dialogues. New questions for se in the course of daily instruction. We have boratory setting a fruitful environment for de- ing, and modifying our instructional materials ous basis.

s and strategies

gained from our investigations to identify and ific student difficulties have been incorporated *Inquiry*. Over the years we have distilled from of research and from our teaching experience principles that characterize what we believe effective parts of the curriculum we have pro- se these principles here as an organizational or demonstrating how research can contribute m development.

wo principles are broad. They have provided on for the development of *Physics by Inquiry* he structure and spirit of the individual mod- t two principles could also be considered general instructional strategies. We have elevated them to the status of principles because of the key role they have played in the development of our instructional materials. The examples used as illustrations have been drawn from two of our laboratory-based modules, *Kinematics* and *Electric Circuits*. We have deliberately chosen simple illustrations so that attention can be focused on the strategies, rather than on the greater subtleties that might be inherent in more complicated subject matter. Each illustration consists of a specific difficulty and one or more instructional strategies designed to address that difficulty.

1. Concepts, reasoning ability, and representational skills should be developed together in a coherent body of subject matter

A major principle followed in designing *Physics by Inquiry* is that concepts, reasoning ability, and representational skills should be developed together in a coherent body of subject matter. Each of the individual modules is unified through its focus on a set of related concepts and emphasizes a particular reasoning or representational skill.

It has been our experience that it is necessary for students to develop their understanding of a concept in stages, not all at once. In all our instructional materials, we endeavor to spiral back to the same concepts at gradually increasing levels of complexity. Refinement of a concept takes place as students recognize the need. We also realize that students tend to compartmentalize knowledge. They have difficulty in separating a concept or a process from the context in which it was initially presented. Unless students are asked to employ the same reasoning and representational skills in more than one situation, they may not be able to transfer these skills from one set of concepts to another. Therefore, all the modules provide practice in some of the same reasoning and representational skills. The opportunity to use the same skills with different subject matter helps students develop the ability to apply their knowledge in different contexts.

2. Physics should be taught as a process of inquiry, not as an inert body of information

The second major principle that has guided the design of *Physics by Inquiry* is that physics should be taught as a process, not as an inert body of information. There are a number of articles in the literature that describe this type of instruction.[9] It is not possible here to discuss the teaching of physics as inquiry in any depth. However, the specific examples used below to illustrate some of the principles and strategies that have characterized our curriculum development may give some sense of the inquiry-oriented learning environment for which the modules are designed.

3. The ability to make connections between the formalism of physics and real world phenomena needs to be expressly developed

A third principle that has guided the design of the curriculum is that the ability of students to connect the formalism and experimental techniques of physics with real world phenomena needs to be expressly developed. We know from both research and teaching experience that students often have great difficulty in relating physical concepts and their representations to actual objects and events. The implementation of this third principle in the curriculum is

illustrated below by an example drawn from an investigation of student understanding of motion graphs.

In a descriptive study that extended over several years, the Physics Education Group examined student understanding of motion graphs.[10] The investigation took place in the context of a laboratory-based course taught by members of our group. The following example is taken from research that was an extension of that study.[11]

a. Example from research: failure to sketch a qualitatively correct set of motion graphs for an observed motion. Students taking the calculus-based physics course were given the diagram of the ball and track shown in Fig. 2, accompanied by the following description of the motion: The ball moves with steady speed along the level segment, speeds up down the incline, and then continues at a higher constant speed along the last segment. The students were told that position, s, was measured along the track and were asked to sketch position, velocity, and acceleration versus time graphs for the motion of the ball. Only one of the 118 students gave the correct response shown in Fig. 2.

The results of this study illustrate some of the difficulties students have in relating actual motions to their graphical representations. Several different types of errors were made that indicated an inability to relate features of a graph with corresponding characteristics of the actual motion. For example, all but one student neglected the fact that each segment of the motion takes place in a shorter time interval than the preceding one. There were many other more serious errors. One frequent type was an apparent attempt to emulate the appearance of the track in the shape of the graphs. For example, half of the students represented the motion along the straight inclined track by a straight line on the s vs t graph instead of a curved line. Almost as many drew parallel lines for the first and third segments of that graph, perhaps because the corresponding track segments were parallel in space. The ability to make connections between an observed motion and its graphical representation does not develop spontaneously with the acquisition of graphing skills. Such facility must be expressly cultivated.

b. Instructional strategy: provide practice in translating back and forth from motion to graphs and from graphs to motion. We believe that the most effective way to help students learn to represent and interpret an actual motion in terms of various types of motion graphs is through experience in the laboratory.[12] In the *Kinematics* module from *Physics by Inquiry*, students are required to translate back and forth from motion to graphs and from graphs to motion. They are given a great deal of practice in sketching qualitative graphs of motions that they observe, such as the motion of a ball rolling along various arrangements of straight and inclined track segments. The students are asked to produce position, velocity, and acceleration versus time graphs and to interpret corresponding features on all three types of graphs. They also carry out the graphing process in reverse, i.e., interpret the motion represented on a graph and construct a track arrangement on which a rolling ball will reproduce that motion. Translating back and forth from tracks to graphs and from graphs to tracks helps strengthen the graphing skills needed for proceeding in either direction. Being able to proceed in either direction also helps students improve their ability to relate various features of a motion graph with the characteristics of an actual motion.

The students perform many other types of experiments in which they must make explicit the relationship between an actual motion and its various graphical representations. In addition to performing experiments in which they observe the motion of objects, students generate graphs of their own motions. For this purpose, they use the microcomputer-based laboratory (MBL) motion detector developed by Tinker and Thornton.[13] In analyzing what they must do with their bodies to produce a particular graph, they strengthen their ability to relate the features of a motion graph to the corresponding characteristics of a real motion.

Once students have developed facility in graphing motions in the laboratory, we offer them the opportunity to strengthen this skill through practice on the computer. David Trowbridge, a member of our group for many years, designed a program that implements on the computer exercises similar to those in the *Kinematics* module. In this program, which is entitled *Graphs and Tracks*, the motion of a ball rolling on a set of tracks in the laboratory is simulated on the computer screen.[14] The program provides students with practice in translating in both directions between a simulated motion on the computer screen and the s vs t, v vs t and a vs t graphs that represent the motion.

Graphs and Tracks is an example of software that has been strongly influenced by research.[15] The original design was guided by results from our investigation of student understanding of motion graphs, as well as by experience in using the *Kinematics* module with students in the laboratory. However, research continued to play a role throughout the entire period of development. To a large extent, the feedback provided to students by the program was shaped by an ongoing investigation in which the interaction of students with the computer was carefully monitored. The information obtained was used to make improvements in the program.

4. Certain common difficulties that students encounter in physics need to be explicitly addressed

A fourth principle that has guided the design of *Physics by Inquiry* is that certain common difficulties that students encounter in physics need to be explicitly addressed. Some misconceptions are sufficiently serious that meaningful learning is precluded, even though performance on quantitative problems may not be affected. Although a concep-

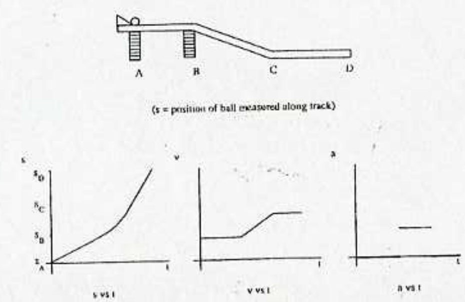


Fig. 2. Track arrangements for which students must produce position versus time, velocity versus time, and acceleration versus time graphs. The correct response is illustrated. The time interval over which the acceleration changes is too small to be visible on the time scale represented.

ing difficulty may be prevalent among stu- e latent and thus not readily apparent either he instructor. Some misconceptions may be experience. Others may result from a misin- f previous experience. In such cases, a mis- y take on the strength of a belief. Difficulties ve proved to be highly resistant to conven- ion.

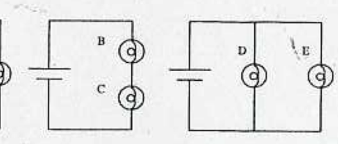
e the need to address certain types of difficul- by an example involving simple dc circuits. small study by our group are consistent with ner investigators that there are a number of s about electric current that are apparently addressed in traditional courses.

from research: failure to rank bulbs in 3 sim- n order of brightness. Students at the Univer- gton who were enrolled in large lecture sec- lus-based and algebra-based introductory sked to respond to the following question as ar course examination. They were presented for three simple circuits in which an ideal nnected across: a single bulb, two bulbs in bulbs in parallel. (See Fig. 3.) The students, pleted the material on electric circuits and re asked to rank the bulbs in order of bright-

ne relative brightness, it is sufficient to think mple model for electric current in which the circuit connected across a battery deter- nitude of the current through that branch. s are required. With the assumption that the ent, the brighter the bulb, it follows that the) and the two bulbs in parallel (Bulb D and ually bright, and brighter than the two bulbs B and Bulb C), which are equal in bright- her.

instructors, who were not members of our sitant about including such a simple prob- nination because they felt that it would not inate among the students. It turned out that as justified, but not for the reason that con- ructors. In the algebra-based course, out of ly 10% responded correctly. In the calcu- e, out of 135 students, only 15% were able bs in the proper order.

ifficulties: common misconceptions about . Almost every possible ranking of the bulbs answers. Analysis of the responses indicat- ents had a number of conceptual difficulties d to their failure to respond to the question were able to identify several common mis- t have also been identified by other investi-



Correct response:
D = E = A > B = C

bs in the circuits according to brightness.

gators. These include the following: Current is used up by the bulbs in a circuit; the battery is a constant current source; the direction of the current, the order to the elements, and the physical placement of the elements all matter.

There was ample evidence that many students misunderstood the concept of equivalent resistance. About 40% of the students attempted to calculate an equivalent resistance for each circuit and then to substitute the value obtained in the power formula. Although no numbers were given in the statement of the problem, some of the students made up their own numbers. The answer obtained for the power depended on which form of the formula (i.e., IV, I^2R, V^2/R) the students chose. The different forms yield different answers when the equivalent resistance is used incorrectly. Inconsistent values were often used for the current, voltage, and resistance. Many students did not realize that to find the brightness of a given bulb its own resistance must be used together with the current or voltage associated with that resistance. The equivalent resistance is useful only for finding the total current through the branch.

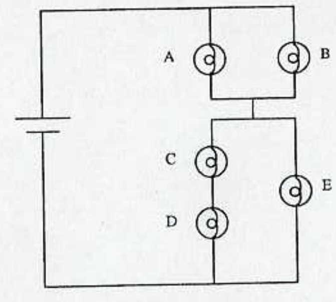
(ii) General difficulty: lack of a conceptual model for an electric circuit. The students revealed in their written responses that they lacked a conceptual model that would enable them to make correct qualitative predictions about the behavior of a simple circuit. However, even without a model they should have been able to answer the question correctly. They had the necessary mathematical skills and had used Ohm's law in problems involving more complicated circuits. Although not strictly appropriate, correct use of the formula would have resulted in the proper relative ranking of bulb brightness. Faced with a simple but unanticipated situation, the students could not do the necessary reasoning.

b. Instructional strategies. We have found that many students lack experience with simple circuits that they can draw upon to help them relate current, voltage, and resistance to actual phenomena that these concepts can be used to explain. Students rarely, on their own initiative, synthesize these concepts into a model that they can use to predict the effect in a circuit of a change in an element.

(i) General instructional strategy: develop a model from laboratory experience. An effective general strategy for helping students understand the relationships among current, voltage, and resistance is to have them develop these basic electrical concepts from direct "hands-on" experience with batteries and bulbs. In the module on *Electric Circuits*, students use both deductive and inductive reasoning to develop a model based on their own observations that they can use to predict and explain the behavior of bulbs in circuits of different configurations.

We have found that students without strong quantitative skills can succeed in constructing a model for electric current that enables them to determine the relative brightness of bulbs in relatively complicated circuits. An additional benefit is that through this experience they gain insight into the nature of a scientific model: what it is, how it can be constructed, how it can be used, and what its limitations are.

After working through the module, elementary school teachers in our courses develop sufficient competence in model-based reasoning to analyze the circuit shown in Fig. 4. To make a correct prediction, it is necessary to recognize that the current through Bulb E is more than half of the current through the battery. Since Bulb A and Bulb B each



Correct response:
E > A = B > C = D

Fig. 4. Rank the bulbs in the circuit according to brightness.

receive half of the current through the battery, they are equally bright but not as bright as Bulb E. Bulb C and Bulb D each have the same current, but since it is less than half of the current through the battery, these bulbs will be of equal brightness but dimmer than the others. We believed that being able to make a correct qualitative prediction for this circuit is indicative of a higher level of conceptual understanding than merely being able to manipulate the algebraic symbols in Ohm's law successfully.

(ii) Specific instructional strategy. The process of constructing a model provides many opportunities for students to correct, on their own, some mistaken ideas they have concerning electric circuits. However, there are difficulties for which no significant conceptual change appears to take place unless students become engaged at a deep intellectual level. Several misconceptions about electric circuits seem to be of this type. To secure the active involvement of students in overcoming some specific difficulties that have proved highly resistant to instruction, the curriculum makes frequent use of a strategy in which the tendency to make a particular error is deliberately exposed. The underlying conceptual or reasoning difficulty is then explicitly addressed. The procedure may be summarized as a sequence of steps that might be characterized in some instances as: observe, recognize, apply; and in others as: elicit, confront, resolve. It should be emphasized that these are not distinct strategies, but are part of a continuum in which there is considerable overlap.

(a) Observe, recognize, apply. At a point in the module when the students have acquired some experience with bulbs in series, the assumption is introduced that the brightness of a bulb is an indicator of the amount of the current. The students then do some exploratory experiments with parallel connections. They compare the brightness of a single bulb in a circuit with the brightness of each of the bulbs in a parallel combination. The students are then asked to use their observation that all the bulbs are equally bright to determine the relative amounts of current through the battery in the two circuits. In attempting to respond to this question, the students begin to consider the implications of their observation. The common belief that the battery is a constant current source is virtually always evoked.

The following statement is an almost verbatim reproduction of a remark made by a high-school teacher during a recent workshop. The comment illustrates the kind of reac-

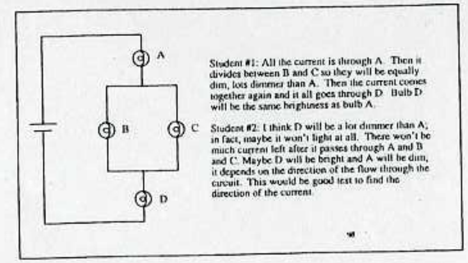


Fig. 5. Example of student dialogue from the *Electric Circuits* module.

tion the teaching sequence is meant to generate: "That would mean that the amount of current from the battery is different in different cases and that doesn't make any sense!" This recognition is a first step in the process of helping students accept the idea that the current through the battery is not constant. It has been our experience that it takes many such encounters to convince students that the current through the battery depends on the number and on the arrangement of the bulbs in the circuit. Unless students are required to apply this idea in many different situations, however, they are likely to revert to their original belief that the current through the battery is constant.

(b) Elicit, confront, resolve. Another version of the same basic instructional strategy is used in *Electric Circuits* after students have had considerable experience in experimenting with various combinations of bulbs. The exercise that follows is designed to elicit the lingering misconception that current is used up by the resistances in the circuit. This mistaken belief has already been addressed earlier in the curriculum but experience has shown that it may still be latent in many students.

The students are presented with the text of a dialogue between two students, in which each makes a different prediction about the brightness of the bulbs in the circuit shown in Fig. 5. The students are asked to state with which student they agree and to give reasons for their choice. Student No. 1 gives a correct analysis, whereas the statement by Student No. 2 indicates that belief that current is used up and that bulb order matters.

The arguments for both the correct and incorrect predictions are clearly articulated in the dialogue. Students who harbor serious misconceptions can seldom state them unambiguously. By making the reasoning that is being used clear, the dialogue helps students confront the incorrect reasoning of Student No. 2. By being asked to contrast the statements, the students must try to resolve the issue. After they have committed themselves to one side of the argument or the other, the students are asked to perform the experiment and reconcile their observations with the position they took on the dialogue.

C. Adaptation of instructional strategies

Although the modules developed by our group are primarily intended for an inquiry-oriented course, many of the instructional strategies can be adapted for use in the lectures, discussion sections, and laboratories that are usually associated with the teaching of introductory physics. For example, all the "hands-on" experiences described in this section could be adapted for use in a laboratory or

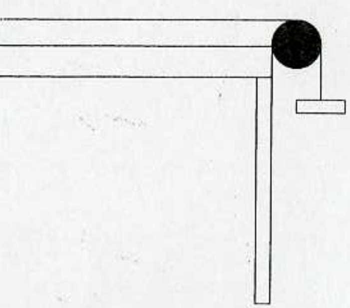
on section to provide a focus for discussion. lialogue could be used as the basis for a ques- work or an examination in a large course. It is wever, that students be required to explain ng, preferably in their own words. Short-an- lse, or multiple-choice tests are not nearly as ssessing understanding at the level involved. nal strategies that have been illustrated share characteristic of encouraging students to ssues that they might not consider without ntion by the curriculum and by the instruc-

ICATION OF THE TRADITIONAL UM

n of the traditional curriculum is another di- he Physics Education Group is taking in re- cognize that widespread adoption of a labora- rriculum is not feasible in courses with large To increase the likelihood that results from benefit a significant number of students, it is take a pragmatic approach that is directed g incremental changes. In some recent inves- begin with the traditional curriculum and ex- ct on students of individual elements of stan- instruction. We try to determine whether sed example problems, lecture demonstra- tory experiments, and computer materials xtend conceptual understanding or whether e additional complexity for students and be- cases to be memorized. In trying to develop a that we can use as a guide for making modifi- ditional instruction, we are taking what we terize as a "top-down" approach, i.e., pro- the existing curriculum and trying to improve students.

rom traditional curriculum: The modified hine

te this new direction in our research through mple: the modified Atwood's machine. (See articular example has been chosen because of plays in the traditional introductory physics version of the setup appears in one or more



twood's machine.

forms in every introductory course: as an example problem in lecture, as a homework or examination problem, as a lecture demonstration, or as a laboratory experiment. The modified Atwood's machine is often used as the first illustration of how the second law of motion can be applied to a system of two objects in which the motion of one is affected by the other. Thus it is important for instructors to be aware of any complications that might detract from its function in helping students deepen and extend their understanding of dynamics.

The modified Atwood's machine offers a rich context for research on student understanding of mechanics. An analysis of the motion involves all three of Newton's laws. The motion is in two dimensions and depends on interactions among four bodies: the hanging block, the sliding block, the Earth, and the table. The concept of a system must be applied in different ways depending on what information is sought. Simultaneous equations may be involved. Many different concepts from both kinematics and dynamics enter into the analysis. In short, the problem is complicated.

The typical presentation of the modified Atwood's machine in a text or lecture begins with a verbal description and pictorial diagram of the setup. The description includes abstractions that may not have much meaning for the student: a massless, inextensible string and a massless, frictionless pulley. The modified Atwood's machine may be the first problem in the course that explicitly involves the tension in a string.

In spite of the inherent complexity, the question asked is straightfoward: Find the accelerations of the masses and (usually) the tension in the string. To a physicist, it is immediately obvious that the entire system moves with the same acceleration and that there is an unbalanced force in the direction of the acceleration. The procedure for solving the problem is virtually automatic: Draw the appropriate free-body diagrams; then apply the second law. Two different approaches are commonly used.

If only the acceleration is required, the sliding and hanging blocks are frequently treated as a single system moving in one dimension with a single acceleration. Although not rigorous and clear-cut, this simplification seems reasonable and intuitive. The inextensibility of the string insures that the accelerations of both blocks, although different in direction, are equal in magnitude. If there is no friction, this condition renders the modified Atwood's machine essentially equivalent to a system of two bodies accelerated horizontally by a single force equal to the weight of the hanging block. Application of the second law to the compound system yields an equation for the acceleration.

If the tension in the string is also desired, then the hanging and sliding blocks must be considered as separate systems. Application of the second law to each block produces a set of simultaneous equations that can be solved for the acceleration and the tension. A glance at the solution indicates that the magnitude of the acceleration is always less than that of free fall. If the acceleration is not zero, it is also immediately apparent that the weight of the hanging block must be greater than the tension in the string.

The typical laboratory experiment on the modified Atwood's machine resembles the problem-solving exercise. the same basic setup is involved, although the block may slide on an air track instead of the table. The students are usually told which variables to measure and given directions about how these measurements should be made. Data are obtained and perhaps graphed, either by the students or by a computer interfaced with the air track. When the data have been reduced to a form in which a correspondence can be made between numerical values of the acceleration and the tension, it is a common practice to ask students to verify the formal mathematical relationship.

Once the equations have been introduced, whether in lecture or in the laboratory, there is a common tendency to avoid thinking critically about the physical situation. When asked to determine what effect certain changes in the system have on the motion, most students focus on the algebra rather than try to reason qualitatively. As a result they generally fail to recognize two important implications of the second law: (1) The presence of an acceleration indicates that an unbalanced force is acting in the same direction as the acceleration; and (2) the existence of a constraining force (in this case, the tension) limits the magnitude of this acceleration to a value smaller than in free fall.

B. Investigation of student difficulties

We began our investigation of student understanding of the motion of a modified Atwood's machine by conducting individual demonstration interviews in which we tried to identify which aspects seem to cause students the most trouble. We consider the work thus far as a preliminary study. Mark Somers, Peter Shaffer, and other members of the group are in the process of extending the scope and depth of the research.

1. Informal survey

An informal survey conducted by A. Arons in the years between 1968 and 1972 provided some clues on how we might proceed in our investigation. Arons had posed the following question to about 15 graduate students:

How does the force the string exerts on the cart (sliding block) compare with the weight of the hanging block? "Compare" means equal, greater, or smaller.[16]

Initially, nearly all said that the two forces were equal in magnitude. When asked if they would like to change their response, only 30% did so. There is virtually no doubt that all these students could have worked a quantitative problem and gotten a numerically correct answer. However, their qualitative understanding was not sufficiently strong for them to recognize the correct answer without referring to equations.

2. Systematic study

We have conducted formal interviews based on both real equipment and computer simulations. Here we emphasize the research conducted in a laboratory setting. However, interviews utilizing the computer were begun first. Since the simulations and procedures used in this exploratory work strongly influenced the design of the laboratory-based interviews, we note a few relevant features of the computer program. Written by Diane Grayson expressly for the purpose of investigating student understanding of dynamics, the program involved both a simulation of the motion of a single modified Atwood's machine and a simulation of the simultaneous motion of two such machines.[17] The machines were placed end to end so that the two sliding blocks moved toward each other as the two hanging blocks moved downward. Either one machine or both could be shown on the screen.

We attempted to replicate the apparatus and questioning protocol used on the computer as closely as possible in the laboratory-based interviews. We were interested not only in pursuing our main objective (i.e., probing conceptual understanding) but also in exploring whether results obtained with real equipment and computer simulations would be similar. In the laboratory demonstration, two modified Atwood's machines moved on air tracks placed side by side on a table. Each machine consisted of a glider and hanger to which different masses could be added. The two objects were connected by a light nylon thread, which passed over a small frictionless pulley. The length of the thread was the same for both machines and was adjusted so that the glider arrived at the end of the air track when the loaded hanger reached the floor. As the two loaded hangers moved downward, the two gliders moved parallel to each other. With the air off, friction was present; with the air on, there was essentially no friction. One machine could be operated alone or both could be run simultaneously.

The students participating in the interviews were volunteers who had completed the relevant material in the course. Some had also performed the modified Atwood's machine experiment in the laboratory course. The tasks presented to the students required predictions and explanations of the effect on the motion of various alterations that could be made to one or both machines. A brief discussion of the first two tasks in the laboratory-based interviews can serve to illustrate the nature of the research.

The first task involved a single Atwood's machine. The interview began with the mass of the glider at 300 g and the mass of the loaded hanger at 600 g. The air was turned off so that friction was present. After being shown the stationary system, the student was asked what would happen when the glider was released. The typical response was that the hanger would fall and the glider would move along the air track. The student was then asked to describe the motion more precisely, e.g., to state whether the speed would change and, if so, how it would change. The investigator asked additional questions designed to elicit the student's ideas about force and motion. The glider was then released and the student was asked to describe the motion. If the prediction and observation differed, the student had to try to account for the discrepancy.

The second task was a comparison task and involved both modified Atwood's machines. Since they were connected by threads of equal length, when the two gliders were at the same distance from the pulleys, the loaded hangers were at the same height. The mass of the glider in each system was 300 g; the mass of the hanger was 600 g in one system and 400 g in the other. The air was turned off so that friction was present in both systems. The students were asked to compare the motion of the two loaded hangers and the two gliders when the machines were run simultaneously. The comparisons were used as a basis for continuing the dialogue about the relationship between force and motion that was begun during the first task.

C. Identification of specific difficulties

From the performance of the students on these two tasks, as well as on the others that were included in the investigation, we were able to identify several types of conceptual and reasoning difficulties. Below we discuss four related errors that seem especially significant. In the headings below, these are characterized in terms of a hanging

sliding block, the objects typically shown in the modified Atwood's machine. In the discus- interviews, however, we refer to the loaded the glider, the objects that the students actually

recognize that the magnitudes of the velocity ation of the hanging and sliding blocks must

modified Atwood's machine is presented as blem or a laboratory experiment, it is assumed vious to students that the motion of the loaded glider are the same. In fact, we found that about tudents claimed at some point in the interview gnitudes of the velocity or acceleration differed objects. Their explanations showed that the nfusion was not purely kinematical. Generally idence of difficulties with dynamics, including of those illustrated below. Unless students un- t the magnitudes of the velocity and accelera- the same for the loaded hanger and glider, analyze the motion of this two-body system

distinguish between the weight of the ck and the tension and to recognize that the the weight, act on the sliding block

s made by many of the students during the ggested that they might not be distinguishing weight of the loaded hanger and the tension in hese students did not seem to recognize the two forces. If students think of the weight of nger as acting directly on the glider, they may he mass of the loaded hanger as part of the at is being accelerated. Under these circum- the mass of the glider is less than the mass of nger (as in the first two tasks), students may e for the acceleration of the glider that is the gravitational acceleration. On the basis of on, some students concluded during the inter- magnitudes of the acceleration of the glider ded hanger were different. The fact that they his result troubling is an indication that the sumption of the effect that the string has on not obvious to students.

recognize that the tension acts on the k while it is falling and thus the must be less than that of free fall

ents did not seem to recognize that the string pward on the loaded hanger while it was fall- view excerpt below illustrates a typical line of which the tension acting on the loaded hanger ter watching a demonstration of the motion dified Atwood's machine with friction pres- nt was presented with a comparison task in ger masses for the two machines were differ- ent was asked to make a prediction about the n of the two systems.

I'd say that the heavier one (hanger) would lider) faster than the lighter one, but then I w... I keep on thinking back to the Tower of Pisa, you know, when he dropped the small rock and the big rock and they both fell and hit the ground at the same time.

In trying to make a prediction, this student tried to relate the motion to a well known, historical experiment that demonstrates that objects fall at the same rate regardless of their mass. Although the student thought that this experiment was relevant, it was not. The student was not discriminating between free fall and fall constrained by a string.

4. Failure to recognize that the weight of the hanging block must be greater than the tension when the system is accelerating

Many students did not recognize that the acceleration of the loaded hanger downward meant that its weight had to be greater than the tension in the string. Students who do not realize that an acceleration in a given direction indicates the presence of an unbalanced force in the same direction miss perhaps the most important point that an analysis of the modified Atwood's machine can be used to illustrate and reinforce.

D. Implications for curriculum development

Whether in the form of a quantitative problem or a laboratory experiment, the typical presentation of the modified Atwood's machine does not usually engage students at a deep intellectual level. The types of questions that can strengthen conceptual understanding are seldom posed in the traditional curriculum. When they are, it is often under circumstances in which a correct response does not require much serious thought. For example, if students have ready access to the equations, they need only do a routine substitution to determine how the weight of the hanging block compares to the tension or how the magnitude of the acceleration compares with that of the gravitational acceleration.

Many of the difficulties identified during the interviews relate directly to the tension and the acceleration. These are precisely the unknown quantities that students are asked to find in the typical Atwood's machine problem or experiment. However, in the usual presentation of this material, little attention is given to helping students confront and resolve these difficulties. Thus study of the modified Atwood's machine often does not deepen conceptual understanding of the laws of motion. For many students, the complications introduced merely increase the confusion. If the problem is to serve its primary purpose, the more serious difficulties must be expressly addressed.

We have not yet produced instructional materials based on the results of the research discussed in this section. We might begin, as we have done in the past, by modifying the tasks from the interviews. Various versions could be readily incorporated into problems, demonstrations, or laboratory experiments. We have found that questions that provide us with insight into student understanding in our research can often serve as a basis for the design of effective instructional strategies to address specific difficulties.

We could, of course, respond in a different way to the findings from our research. Another option would be to omit the modified Atwood's machine because of its complexity. However, we think that this topic from the traditional curriculum offers a good opportunity for concept development that should be exploited rather than ignored.

VIII. INVESTIGATION OF THE POTENTIAL OF THE COMPUTER

For the past few years, the Physics Education Group has been engaged in investigating the potential of the computer for improving physics education. We have been exploring the use of the computer both as a medium of instruction and as a probe of student understanding. This direction in our research has been described in some detail in several articles in the *American Journal of Physics*.[15] We shall not discuss that work here except to comment on a few features relevant to some issues that have been raised.

Since the development of *Graphs and Tracks* was strongly influenced by the research and curriculum development of our group, we decided to see whether the program, in turn, could help us gain additional insights into the difficulties students have in drawing and interpreting motion graphs. Grayson conducted a series of interviews in which she utilized the program to probe student understanding of the graphical representation of motion.[15]

A. Comparison between results from real and simulated motions

When we compared the results from the computer-based interviews with findings from a descriptive study conducted during laboratory-based instruction, we found many similarities.[15] For the most part, we identified the same conceptual and reasoning difficulties in both situations. There were some differences, however.

The computer made it possible for us to explore certain difficulties of a semiquantitative nature that we had not been able to observe during instruction. We were also able to take advantage of the immediate feedback that the computer provided to students. Since they had a visual means for deciding whether or not a response was correct, the investigator did not have to interrupt the students' train of thought as much as might have been required in the laboratory. From watching how the students attempted to correct errors, we could infer the relationship they perceived between the features of a graph and the characteristics of the motion represented by that graph. In addition to the information obtained during the formal interviews, we obtain additional insights from informal observations of students while they used *Graphs and Tracks* in class.

Most of the differences that we found between student response to *Graphs and Tracks* and to real equipment in the laboratory were small. However, one problem emerged from the study that is a cause for concern. It is the difficulty of determining the degree of intellectual engagement of the student. Even a highly interactive program such as *Graphs and Tracks* does not insure that student attention is at a sufficiently deep level for meaningful learning to take place. Informal observation during class indicated that for some students the task of obtaining a match between a track arrangement and a graph seemed to take on the aspect of a game. They were invariably pleased when they succeeded but, on questioning by the instructor, could not explain how they had determined what to do to construct an appropriate graph or track arrangement.

The experience with *Graphs and Tracks* indicated that students may not react in the same way to a computer simulation as they do to laboratory equipment. Results from the laboratory-based and computer-based interviews on the modified Atwood's machine and the computer simulation were very similar, but not identical. In the laboratory, the gliders moved parallel to each other, whereas on the computer, the sliding blocks moved toward each other. In the laboratory, the size of the apparatus precluded the student from viewing both the hanger and glider motion simultaneously. On the computer, both motions were easily viewed together. Another difference was that the natural motion in the laboratory was considerably faster than the simulation on the computer. There were other small differences: clutter in the laboratory as opposed to sharp graphics on the computer screen, a three-dimensional instead of a two-dimensional setup, a slightly sagging thread instead of an idealized representation of a straight string.

Essentially the same student difficulties were identified in the laboratory-based and computer-based interviews. However, as with *Graphs and Tracks*, there were a few exceptions. The most significant difference was that about half of the students who participated in the laboratory-based interviews stated at some point during the interview that the hanger and glider for a single Atwood's machine differed in some way in their motion. For some, the statement seemed to be the result of an observation they had made. However, during the computer-based interviews, no student claimed that the velocity and acceleration were different for the hanger and glider.

B. Need for caution in the use of computer-based instruction

The differences between student performance in the laboratory and on the computer suggest certain concerns that need to be addressed when we contemplate the use of computer-based instruction. Two are considered here. One follows directly from the discussion above; the other is less obvious.

Even a highly interactive computer program provides no guarantee that students will be engaged at a sufficiently deep level for significant concept development to occur. Success on a computer task does not necessarily indicate that students have developed a skill that can be transferred to another environment. Unless students can articulate the reasoning that prompted the manipulations made with the mouse or the responses typed on a keyboard, it is difficult to determine if any meaningful learning has taken place.

Our experience with the modified Atwood's machine raises an issue that is more subtle. At first glance, it might seem tempting to dispense with the actual experiment in favor of the computer simulation. The apparatus is not only somewhat awkward to set up but seems to encourage students to make a very serious error that they do not make with the computer simulation. Unless they recognize that both the hanging and sliding blocks must have the same velocity and acceleration, students cannot possibly solve the problem. On more careful reflection, however, we may conclude that confining the students' encounter to the computer and thereby avoiding the error is precisely what we should not do. Since it is not necessary to see either the apparatus or a demonstration to know that the motion of the hanging block and sliding block must be identical, this error indicates a basic lack of understanding that needs to be addressed. Allowing the error to occur and then insisting that students confront and resolve the underlying difficulty is the most effective way of helping them recognize the role of the string.

LUSION

ve that research in physics education can help
attern of curriculum reform, enthusiastic adop-
al disillusionment, and eventual degeneration.
suggested that a major reason for the recurrence
wo stages in the cycle has been that the curricu-
ysics and physical science has not been well
the students or to the instructor, or to both. A
effort to improve the match between students
roductory college curriculum may be of direct
dressing many of the difficulties students have
ourse. Since the enrollment includes prospective
ch an approach may also be an indirect means
ng the mismatch between future teachers and
ge curriculum.

ion of research results to instruction

rom research are a rich resource that textbook
d software developers can draw upon to help
the materials they produce are suitable for the
r whom they are intended. However, the appli-
esearch to instruction should not be limited to
ment of printed and computer materials. Find-
research can be applied directly in classroom

ate use

e at least two ways in which research in physics
an be useful to instructors. One is as a source of
n about specific student difficulties and effective
al strategies. The second application is more di-

found that our investigations of student under-
ovide a good source of ideas for problems, dem-
, and laboratory experiments. The tasks used in
ual demonstration interviews to expose errors
e modified and adapted to fulfill the same func-
instruction. Findings from research can guide
to pretests that can be used before and during
in lecture, laboratory, or discussion sections. If
e quantitative procedures have been presented,
questions that require explanations of reasoning
student interest, focus attention on key issues,
age reflection. For this approach to be effective,
minations must include similar types of ques-
ss students think they have to demonstrate
at a significant conceptual level on tests, most
est the time and effort needed to achieve a high
nastery.

a critical condition that must be met for the type
on described to be effective. A nonpejorative
must be cultivated in the classroom or labora-
kes should be viewed as opportunities to learn,
ts must be given the chance to demonstrate that
earned. The grading system has to be made suffi-
ible to reflect their progress.

riate use

out the discussion, there has been an implicit
out how the results of research should *not* be
ruction. Helping students develop a sound con-
lerstanding is not simply a matter of making a
list of misconceptions and explaining mistakes that they should avoid. There is considerable evidence that students often do not make the same errors under all circumstances. A particular mistake may be evoked under one set of conditions but not under another. The context may be the determining factor. An error may be a symptom of an underlying conceptual difficulty or a reasoning difficulty, or a combination of both. If faulty reasoning lies at the heart of difficulty with a concept, focusing instruction on the concept alone does not provide students with the kind of help needed.

Perhaps the strongest reason for not warning students about common errors is that such an approach is seldom effective. It is generally not very helpful to tell students what mistakes they should not make. The warning is almost always misunderstood. Often an error described by an instructor may appear trivial to a student and thus the warning may be dismissed as irrelevant. Sometimes if students recognize their susceptibility to making a particular error, they may endeavor to suppress the tendency while making a mental note not to make that particular mistake. However, the underlying difficulty that is the real cause of the error may remain latent and surface unexpectedly under another set of circumstances. Conceptual and reasoning difficulties cannot be overcome through assertion by the instructor. Such changes in thinking require a significant intellectual engagement by the student. The only method likely to be effective in addressing serious difficulties is to design instruction to expose them and then to address them specifically, not just once but several times.

A special warning might be added that is relevant to the education of teachers. If they have a tendency to make an error, they must be allowed to do so, or to observe someone else make that error. To prepare them to help their students overcome a specific difficulty, we cannot simply describe an appropriate instructional strategy. Unless they see a strategy in action, they are not likely to be able to implement it in the classroom.

B. Need for research and dissemination of results

Specific examples have been used to illustrate the relationship between research in physics education and curriculum development. The perspective and work of the Physics Education Group have provided the context. The particular context, however, is not critical. What is crucial is that research be conducted by physicists who have thought deeply about the subject matter, who have had experience in teaching the material, and who are willing to focus on students: to listen rather than explain. Furthermore, research should be thought of as including not only the identification of student difficulties but the development of instructional strategies that address them.[18] As much careful testing should go into the design of instructional materials as into generating knowledge of student difficulties. In trying to improve the match between the curriculum and the students, our group has found it fruitful to think of the design of instructional materials as part of an iterative cycle in which research, curriculum development, and instruction mutually reinforce one another. To be useful in helping close the gap between what we teach and what is learned, it is essential that the entire process be iterative.

As in traditional research in physics, the possibility of making significant progress depends on the existence of a community. Research in physics education by investigators with a strong disciplinary orientation is more common abroad than in the United States. There is a need in this country for an active community of physicists who are working in this area. If research is to fulfill its mission of helping to improve the match between the students and the instruction they receive, it is imperative that the results be disseminated not only within the research community but to all who develop curriculum and to all who teach the subject. The presentation of papers at professional meetings is clearly important, but at least as critical is the publication in the physics literature of research reports that meet the standards for evidence and reproducibility that is expected in the areas of research in which physicists have been traditionally engaged.

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[1] *Elementary Science Study* (Education Development Center, Newton, MA); *Science Curriculum Improvement Study* (University of California, Berkeley, CA); *Science—A Process Approach* (American Association for the Advancement of Science, Washington, DC).

[2] M. Neuschatz and M. Covalt, *Physics in the High Schools: Findings from the 1986–1987 Nationwide Survey of Secondary School Teachers of Physics*, AIP Rep. R-340 (American Institute of Physics, New York, 1988), pp. 16–20.

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[5] This premise is examined by S. Tobais in *They're not Dumb, They're Different: Stalking the Second Tier* (Research Corporation, Tucson, AZ, 1990).

[6] A discussion of international contributions to research in the area of conceptual understanding of mechanics can be found in a review by L. C. McDermott, Phys. Today, **37**(7), 24 (1984).

[7] See, for example, D. E. Trowbridge and L. C. McDermott, "Investigation of student understanding of the concept of velocity in one dimension," Am. J. Phys. **48**, 1020–1028 (1980); D. E. Trowbridge and L. C. McDermott, "Investigation of student understanding of the concept of acceleration in one dimension," Am. J. Phys. **49**, 242–253 (1981); R. A. Lawson and L. C. McDermott, "Student understanding of the work-energy and impulse-momentum theorems," Am. J. Phys. **55**, 811–817 (1987); F. M. Goldberg and L. C. McDermott, "Student difficulties in understanding image formation by a plane mirror," Phys. Teach. **24**, 472–480 (1986); F. M. Goldberg and L. C. McDermott, "An investigation of student understanding of the real image formed by a converging lens or concave mirror," Am. J. Phys. **55**, 108–119 (1987).

[8] Some of the individual modules are currently available from the Physics Education Group. *Physics by Inquiry* should soon be available through a commercial publisher. The point of departure for the development of *Physics by Inquiry* was the *The Various Language* by A. B. Arons (Oxford U.P., New York, 1977).

[9] See, for example, A. B. Arons, "Anatomy of a physical science course for non-science students," J. Coll. Sci. Teach. **1**, 30–34 (April 1972); L. C. McDermott, "Combined physics course for future elementary and secondary school teachers," Am. J. Phys. **42**, 668–676 (1974).

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